www.cadanda.com Computer-Aided Design AND APPLICATIONS

Undercut Free Parting Direction Determination for Injection Molded Parts Using Surface Based Accessibility Analysis

Rajnish Bassi[1], Sanjeev Bedi[2] and Gerardo Salas Bolaños[3]

[1]University of Waterloo, r2bassi@engmail.uwaterloo.ca
[2]University of Waterloo, sbedi@mecheng1.uwaterloo.ca
[3]University of Waterloo, gsalas@engmail.uwaterloo.ca

ABSTRACT

A novel approach to determine the undercut free parting direction of a given mold part, in B-rep format, by using the accessibility of each of its surface is presented. The proposed system is designed to classify planar, ruled and freeform part surfaces based upon the criteria of their accessibility relative to the specified directions. The orientation of each surface with respect to the considered direction is used as an input for the accessibility analysis module. To analyze the accessibility, the surfaces are swept in the different directions, based on their orientation, to form solid bodies. A number of regularized boolean operations are performed on the swept bodies. Then, volume and geometry-based constraints are applied to classify the part surfaces based on the accessibility. Using the results of accessibility analysis in a given set of directions, feasible mold parting directions are determined. The method has been successfully implemented and tested on benchmark parts and the results are discussed in this paper.

Keywords: parting direction, surface accessibility, mold design, core/cavity surfaces.
DOI: 10.3722/cadaps.2011.175-191

1 INTRODUCTION

Injection molding is one of the fundamental techniques to produce near-net-shape parts with minimal secondary processes. The simplest molds consist of two pieces, namely, core and cavity. These mold pieces separate in the opposite directions (called parting direction) to remove the part from the mold. However, the complexity of the whole scenario increases due to the presence of the undercuts. To mold a part with undercuts, side or split cores need to be used. In some mold parts, these undercuts can be avoided by simply changing the parting direction as some of the part faces can form an undercut in one parting direction, but not in the other parting direction. Therefore, the focus of the current research is to determine if any direction, out of a given set of directions, is undercut free.

In the proposed methodology, a feasible mold parting direction is determined by evaluating the accessibility of each face of the part from a given set of directions. There have been attempts reported in the literature to use the results of accessibility analysis for determining the presence of the undercuts. A detailed literature review focused on the accessibility analysis to ensure the part demoldability is presented next.

2 LITERATURE REVIEW

Many attempts have been made to automate the parting direction determination process by using different methodologies. In one of the initial attempts, Hui and Tan [5] have used semi-infinite rays originating from the surface grid points toward the chosen parting direction to classify these as obscured or unobstructed. They have defined a factor (called a blocking factor) to determine the extent of blockage along the chosen parting direction.

To determine the best pair of the parting directions, Chen et al. [1] have used the visibility maps to find a pair of antipodal points that covers the maximum number of V-maps of the pockets. Nee et al. [8] determined the optimal pair of parting directions that result in minimizing the sum of possible undercut volumes. Woo [11] have described the importance of the visibility maps in various manufacturing applications including the die and mold design. Chen et al. [2] have used the two levels of visibility, i.e., complete and partial, to determine the condition for demoldability of polyhedral surfaces. Their approach selects the parting direction that minimizes the number of undercuts. Later, Kim et al. [7] developed procedures for constructing tangent, normal and visibility cones for regular Bezier surfaces. Elber and Cohen [6] presented a method to compute the Gauss map (G-Map) of several trimmed freeform surfaces and to compute the set of views from which the chosen surface is locally visible.

Dhaliwal et al. [3] determined the global accessibility cones for all facets of a polyhedral object. The exact inaccessible region for a facet is computed to get the global accessibility cones for all the facets on the object. Priydarshi et al. [9] determined accessibility of each facet along the chosen parting direction by checking the obstruction of each facet with rest of the facets on the object. For near-vertical facets, they have slightly rotated the viewing direction in such a way that near-vertical facet becomes front-facing facet. Their methodology is applicable for polyhedral objects only and a freeform surface needs to be approximated using number of facets. However, number of polyhedral facets required for approximating a freeform surface depends on the required part accuracy.

There have been reported attempts to determine the accessibility with the aid of computer graphics hardware. Khardekar et al. [6] have developed a user routine to set the color and depth by taking its texture and interpolated vertex data as input for the visibility analysis. In their work, they have the tessellated the CAD model to use as an input. Priyadarshi and Gupta [10] have used the graphics hardware capabilities to identify the facets that are inaccessible from the parting direction and are forming the undercuts. The approximations involved in the graphics-hardware-based approach effects its robustness.

It can be observed from the previous discussion that a lot work has been done on analyzing the surface visibility for automating of the injection molding design process. However, most of the work is based on the visibility of various points on a surface from different directions. Ray based visibility analysis approach [1], [2], [5], for classifying the surface based on accessibility, includes the discretizing of the surface into points and firing rays in the parting direction. However, features smaller than the discretization step are lost; additionally, decreasing discretization step size results in large computational time. In the work of some researchers [3], [6], [8-9], the CAD model has been tessellated to use as an input. The accuracy of the visibility analysis depends upon the size of the tessellated triangles. In order to overcome the problems associated with point based methods, a surface based accessibility analysis technique is developed and presented in this paper. Moreover, the current research is focused on determining the accessibility of each face of a B-Rep model without any discretization.

The research objective of this paper is described in Section 3. Various terms used in this paper are defined in Section 4. The overview of procedure and detailed algorithms are given in Section 5 and 6, respectively. The algorithm has been implemented on test parts and the results are discussed in Section 7.

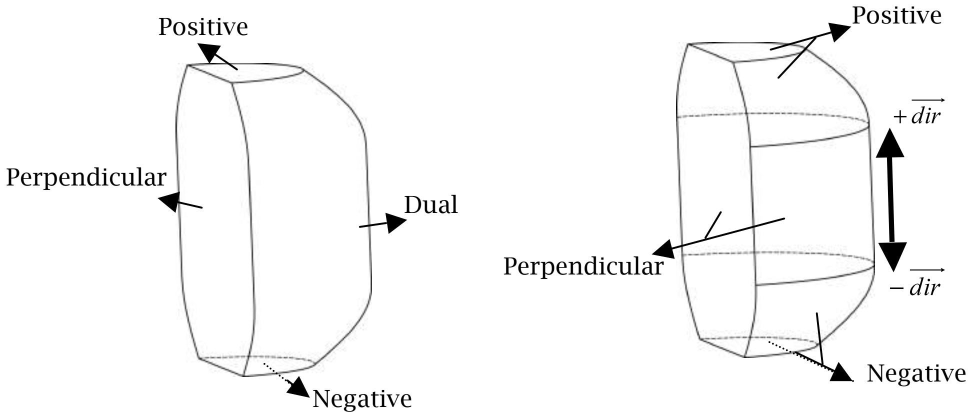
3 PROBLEM FORMULATION

A part face is accessible in a direction if it is not obstructed by any other face in that direction. If all the faces of a part are fully accessible in a direction, then the part can be moldable in that direction without any side-core/cavity. The objective of the present work is to determine the accessibility of each face of the part and to evaluate part de-moldability in the given set of directions.

4 SURFACE CLASSIFICATION TERMS

In two piece conventional molding, core and cavity separate in the opposite direction during demolding. The two sides of the parting direction correspond to separation direction of core and cavity, respectively. One of the two sides of the parting direction is called the positive parting direction ($+\overrightarrow{dir}$) and the other is called the negative parting direction ($-\overrightarrow{dir}$). In the proposed methodology, each direction, out of a set of directions, is evaluated in sequence to determine the part demoldability and is called as the considered parting direction. The orientation of surface normal with respect to the positive side ($+\overrightarrow{dir}$) of the considered parting direction is used for orientation-based classification of each face/surface, discussed in Section 4.1. Next, the surfaces are classified based on accessibility in the considered parting direction, discussed in Section 4.2.

4.1 Orientation Based Surface Classification



(a) Before splitting (b) After splitting

Fig. 1: Orientation based classification.

Surfaces (either freeform or planar) are classified into four categories, shown in Fig. 1, based on the cosine of angle (θ) between surface normal and the considered positive parting direction $+\overrightarrow{dir}$. The criteria for the four categories (positive, negative, perpendicular, and dual) are given in Tab. 1. Most industrial parts have dual surfaces that exhibit characteristics of positive, negative and perpendicular surfaces at different surface points. Such surfaces are divided into positive, negative and perpendicular surfaces by generating the silhouettes in the considered parting direction $\overrightarrow{dir}$, as depicted in Fig. 1 (b).

Surface Type	*Cosine of angle (θ)*
Positive	cosine (θ) > 0
Negative	cosine (θ) < 0
Perpendicular	cosine (θ) = 0
Dual	cosine (θ) >= 0 and cosine (θ) < 0

Tab. 1: Orientation based classification criteria.

4.2 Accessibility Based Surface Classification

To determine demoldability of a part/object (*O*) with respect to the considered parting direction ($\overrightarrow{dir}$), the surfaces of the part are classified based on their accessibility. The terms related to accessibility, shown in Fig. 2, are defined next.

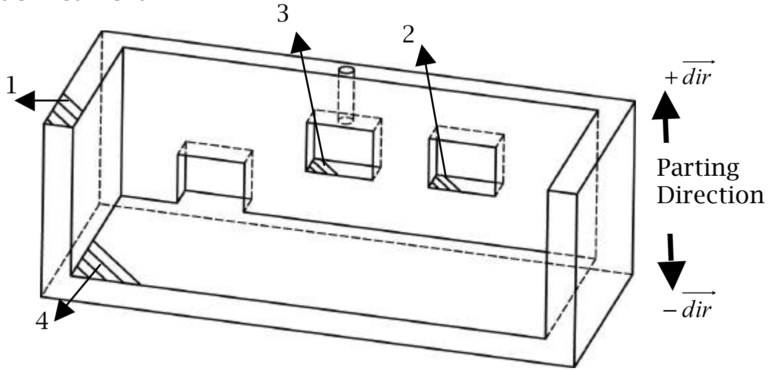


Fig. 2: Accessibility based surface classification of positive and negative surfaces: (1) *Fully-Accessible*, (2) *Fully-Inaccessible*, (3) *Outer-Boundary-Inaccessible* (*Partially-Accessible*), and (4) *Partial-Outer-Boundary-Accessible* (*Partially-Accessible*).

A surface *S* is *Fully-Accessible* from the direction $\overrightarrow{dir}$ if translation of *S* to infinity in $\overrightarrow{dir}$ does not cause any intersection with the interior of the object *O*.

A surface *S* is *Fully-Inaccessible* from the direction $\overrightarrow{dir}$ if translation of *S* to infinity in $\overrightarrow{dir}$ results in intersection of all points on *S* with the interior of the object *O* at least once.

A surface *S* is *Partially-Accessible* from the direction $\overrightarrow{dir}$ if translation of *S* to infinity in $\overrightarrow{dir}$ results in intersection of some points on *S* with the interior of the object *O*.

A surface *S* is *Outer-Boundary-Inaccessible* from the direction $\overrightarrow{dir}$ if translation of *S* to infinity in $\overrightarrow{dir}$ results in intersection of some inside point and all boundary points of *S* with the interior of the object *O*.

A surface S is *Partial-Outer-Boundary-Accessible* from the direction $\overrightarrow{dir}$ if translation of *S* to infinity in $\overrightarrow{dir}$ results in intersection of some inside point and some boundary point of *S* with the interior of object *O*.

To facilitate the analysis of a *Fully-Inaccessible* surface, the surface is categorized into two types: *Type1* and *Type2*. If an inaccessible surface is shadowed by a connected set of interfering surfaces, it is classified as *Type1*, shown in Fig. 3 (a); otherwise, it is classified as *Type2*, shown in Fig. 3 (b) and (c).

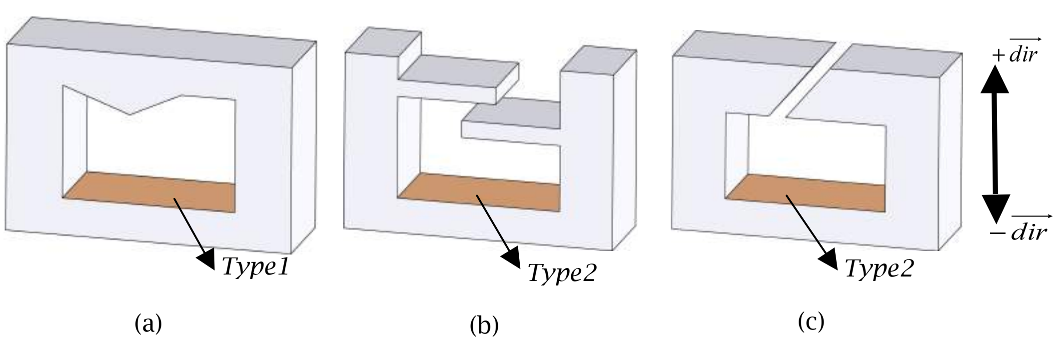


Fig. 3: Inaccessible surfaces classification: (a) *Type1*, (b) and (c) *Type2* inaccessible.

5 OVERVIEW OF TECHNICAL APPROACH

To determine the demoldability of a part in the considered parting direction $\overrightarrow{dir}$, faces of the B-Rep model are first classified based on their orientation with respect to the direction $+\overrightarrow{dir}$, as discussed in Section 4.1, then classified based on accessibility. Orientation based classification is required to avoid unnecessary operations in the accessibility analysis, e.g., surfaces classified as negative cannot be accessible from the $+\overrightarrow{dir}$ direction, therefore, it is not required to check their accessibility from the positive direction.

During accessibility analysis, positive and negative surfaces are mainly classified into three types, namely, *Fully-Accessible*, *Partially-Accessible*, and *Fully-Inaccessible*, shown in Fig. 2. Depending upon the accessibility of the outer edge boundary of the *Partially-Accessible* surfaces, these surfaces are further classified into two types: *Partial-Outer-Boundary-Accessible* and *Outer-Boundary-Inaccessible*. Further classification of the *Partially-Accessible* surfaces can be useful for splitting them into *Fully-Accessible* and *Fully-Inaccessible*, if required.

The perpendicular surfaces can be fully accessible from both positive and negative parting direction, if not obstructed by any other surface. Therefore, perpendicular surfaces are analyzed in both, $+\overrightarrow{dir}$ and $-\overrightarrow{dir}$, directions and are classified in the each direction into three categories: *Fully-Accessible*, *Partially-Accessible*, and *Fully-Inaccessible*, shown in Fig. 4. A *Partially-Accessible* perpendicular surface cannot be *Outer-Boundary-Inaccessible*; therefore, such a surface is not classified further.

This surface classification is used as an input to determine if the considered parting direction is undercut-free and demoldability is possible without side-cores and cavities.

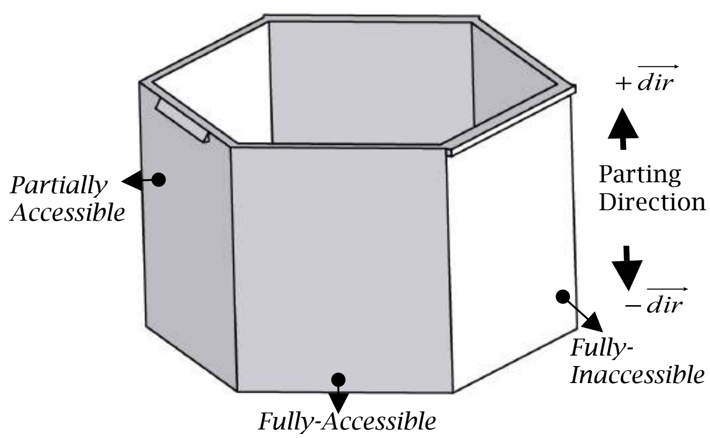


Fig. 4: Accessibility based classification of perpendicular surfaces from $+\overrightarrow{dir}$ direction.

The accessibility analysis is carried out by selecting one surface at a time from a valid solid body and sweeping it in the considered parting direction to check its accessibility. The above approach is similar for determining the accessibility of all types of surfaces under consideration, but, orientation based surface classification is utilized to reduce the lead time in accessibility analysis and is illustrated in Fig. 5.

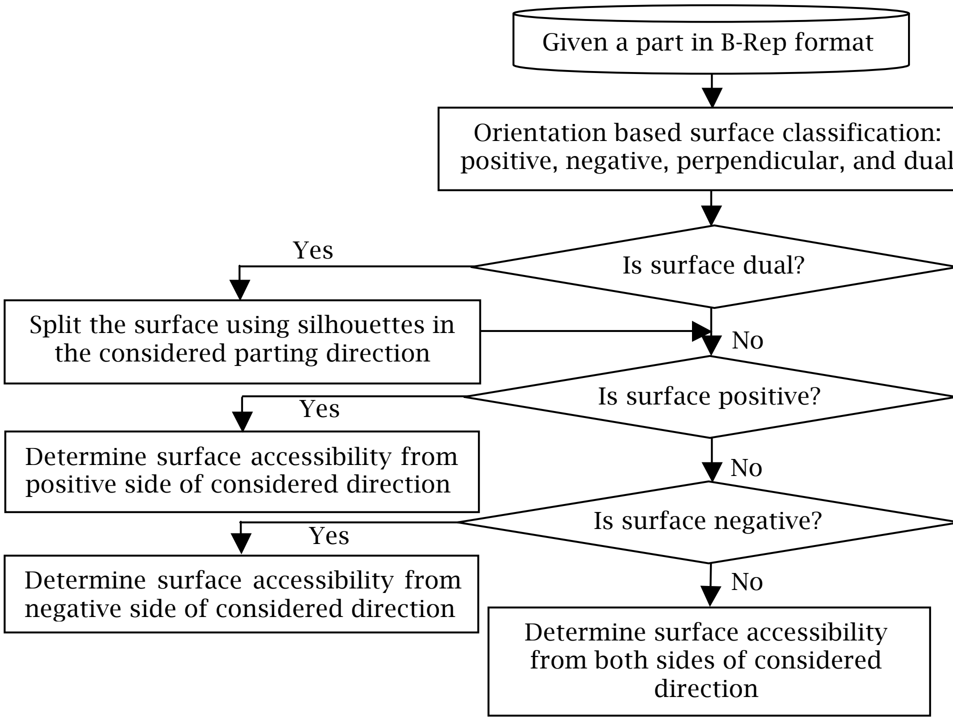


Fig. 5: Role of orientation-based classification during Accessibility analysis.

6 ACCESSIBILITY ANALYSIS METHODOLOGY

The detailed methodology to classify a surface based on its accessibility is illustrated using a test part, shown in Fig. 6, consisting of surfaces with different levels of accessibility from the considered parting direction ($\overrightarrow{dir}$). The methodology adopted for the positive and negative surface is presented first, followed by methodology adopted for the perpendicular surfaces.

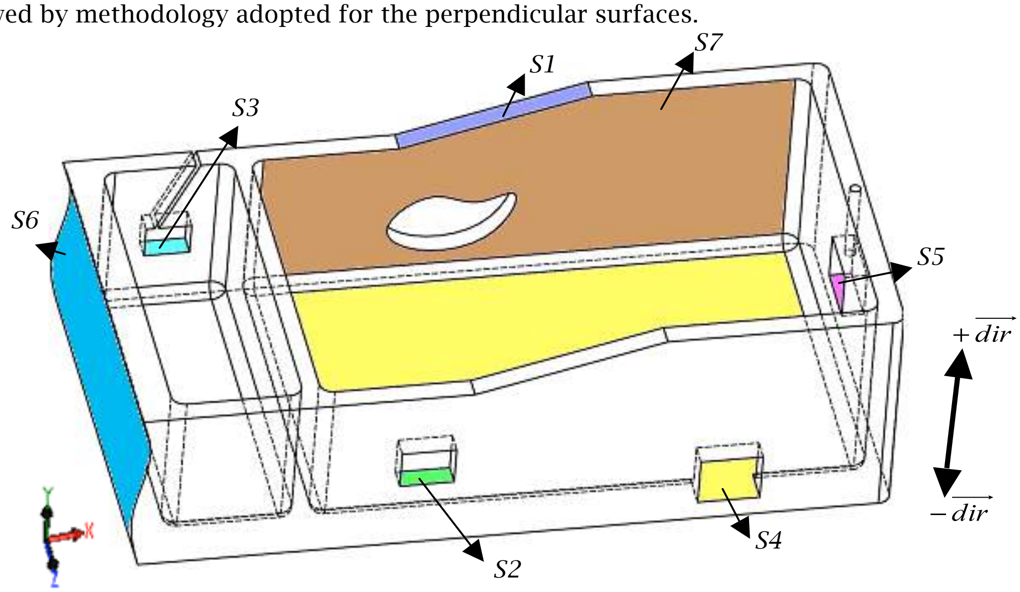


Fig. 6: Test part to illustrate accessibility analysis procedure considering parting direction along Y-axis.

6.1 Positive and Negative Surfaces

Positive and negative surfaces are checked for accessibility in $+\overrightarrow{dir}$ and $-\overrightarrow{dir}$ directions respectively using the same methodology. A series of sweeping and regularized boolean operations, along with the geometrical and topological constraints, are utilized to determine the accessibility level of the considered surface.

6.1.1 Fully-Accessible Surfaces

The considered surface is selected and swept, along the $+\overrightarrow{dir}$ direction if the surface is positive, by a distance more than the maximum dimension (say twice the maximum dimension) of the part in that direction. In case of the negative considered surface, the surface is swept along the $-\overrightarrow{dir}$ direction. The sweeping operation results in a valid solid body *B_Swept1*, shown in Fig. 7(a).

The swept body (*B_Swept1*) corresponds to the space swept by the considered surface during the demolding process. The considered surface will be fully accessible only if there is no interference between *B_Original* and *B_Swept1*. To check the interference, a regularized boolean subtraction operation is performed between *B_Original* and *B_Swept1* as given by the following equation:

$$B\_Result = B\_Original -^{*} B\_Swept1. \tag{1}$$

The above regularized boolean operation represents the subtraction of *B_Swept1* from *B_Original* to generate a resulting body (*B_Result*), as shown in Fig. 7(b). After the regularized boolean operation, the volume of *B_Result* is compared with that of *B_Original*. If both bodies have the same volume, the considered surface is classified as *Fully-Accessible* and no further analysis is performed for this surface.

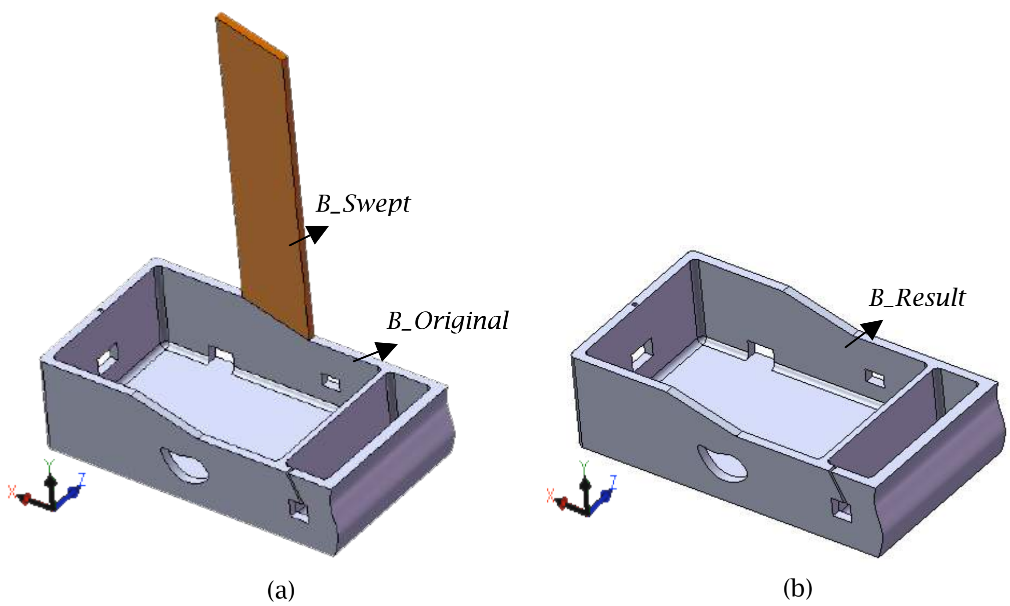


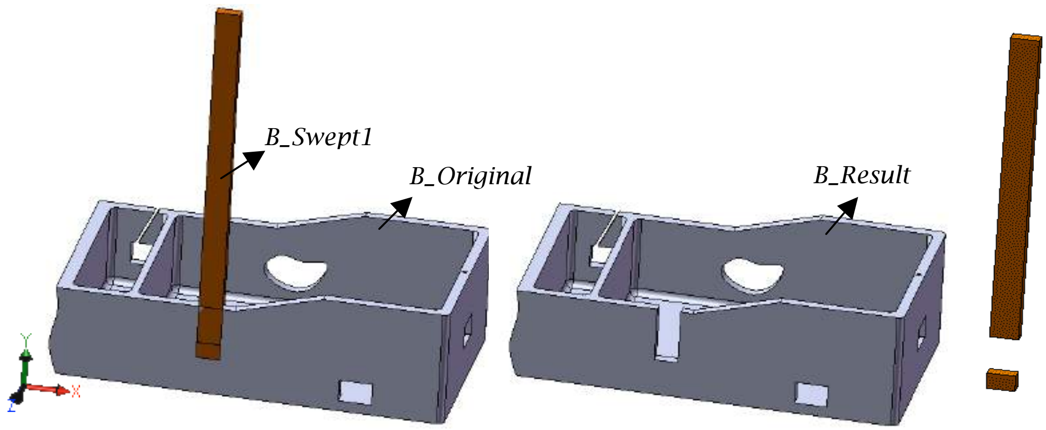
Fig. 7: Accessibility analysis procedure for a *Fully-Accessible* surface, demonstrated using surface *S1* of Fig. 6: (a) *B_Original* and *B_Swept1*, (b) *B_Result* as per Eqn. 1

For example, the sweeping of surface *S1* along $+\overrightarrow{dir}$ direction, in Fig. 7, results in a new swept body *B_Swept1*. The *B_Swept1* does not interfere with *B_Original*. As a result, the resulting body (*B_Result*) has the same volume as that of *B_Original* and the surface is classified as *Fully-Accessible* in the corresponding direction.

6.1.2 Fully-Inaccessible (Type1) Surfaces

If the surface under consideration is not classified as *Fully-Accessible*, then it is tested for the conditions of full inaccessibility and partial accessibility, shown in Fig. 8, from the direction under consideration. Now, a regularized Boolean subtraction similar to Eqn. 1 is used, but *B_Original* is subtracted from *B_Swept1* and is expressed as

$$B\_Result1 = B\_Swept1 -^* B\_Original. \tag{2}$$



(a) (b) (c)

Fig. 8: Accessibility analysis procedure for a *Fully-Inaccessible* surface, demonstrated using surface *S2* of Fig. 6: (a) *B_Original* and*B_Swept1*, (b) *B_Result* as per Eqn. 1, (c) *B_Result1*as per Eqn. 2.

The above boolean operation may result in a number of bodies depending on whether the surface is partially-accessible or fully-inaccessible. If *B_Result1* consists of two or more disjoined bodies, then it is concluded that surface is *Fully-Inaccessible* (*Type1*) from the chosen direction, e.g., the surface considered in Fig. 8 is classified as *Fully-Inaccessible* because the boolean operation, as per Eqn. 2, on *B_Swept1* results in two disjoined bodies, as shown in Fig. 8(c).

6.1.3 Fully-Inaccessible (Type2) and Partially-Accessible Surfaces

If the boolean operation, as per Eqn. 2, results in a single body, as shown in Fig. 9(c), then the considered surface can be *Fully-Inaccessible (Type2)* or *Partially-Accessible*. To analyze the level of inaccessibility, the surfaces of *B_Result1* are classified based on their orientation with respect to the considered positive parting direction. The negative surfaces of *B_Result1*, except the surface corresponding to considered surface, are shown in Fig. 9(d). Dual surfaces in *B_Result1*, if any exists, are segmented into positive and negative surfaces using the silhouettes in the considered direction.

To simplify the explanation, the considered surface is assumed to be positive hereafter. For a positive considered surface, the negative surfaces (one at a time) of the resulting body (*B_Result1*) are swept in the $+\overrightarrow{dir}$ direction, as shown in Fig. 9(e). Negative surfaces of *B_Result1* are swept in previous operation because these correspond to positive surfaces of the original body that can throw their shadow on the considered surface. The sweeping distance of the surface is taken more (say 20 %) than the maximum dimension of the body to which it belongs to. The above operation results in a new body (*B_Swept2*) corresponding to each negative surface of *B_Result1*, as shown in Fig. 9(e). A regularized boolean operation on *B_Result1* and *B_Swept2* is performed as follows:

$$B\_Result2 = B\_Result1 -^* B\_Swept2. \tag{3}$$

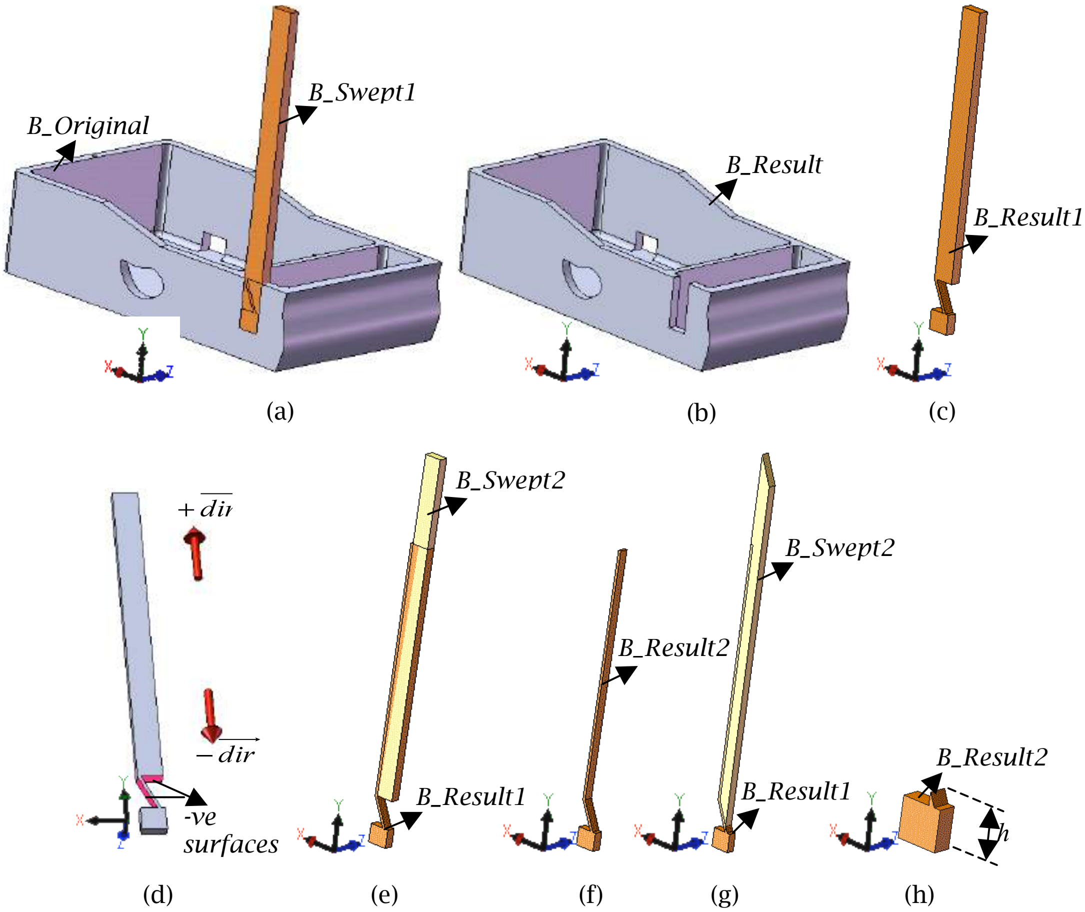


Fig: 9. Accessibility analysis procedure for a *Fully-Inaccessible* surface, demonstrated using surface *S3* of Fig. 6: (a) *B_Original* and *B_Swept1*, (b) *B_Result* as per Eqn. 1, (c) *B_Result1* as per Eqn. 2, (d) -ve surfaces of *B_Result1*, (e) *B_Result1* and *B_Swept2*, (f) *B_Result2* as per Eqn. 3, (g) *B_Result1* and *B_Swept2*, (h) *B_Result2* as per Eqn. 3.

The above operations, including sweeping of negative surfaces and boolean subtraction from the resulting body (*B_Result1*), are repeated until there is any negative surface on the *B_Result2* except the surface corresponding to considered surface. At the end of each cycle, if any negative surface is found on *B_Result2*, then *B_Result2* is renamed as *B_Result1* and the sweeping and boolean subtraction operations are repeated for that surface, shown in Fig. 9(g). Next, if the height (*h*) of *B_Result2*, shown in Fig. 9(h), is less than that of *B_Swept1* in the considered direction, then it is concluded that the considered surface is *Fully-Inaccessible* (*Type2*); otherwise it is classified as *Partially-Accessible*.

6.1.4 Classification of Partially-Accessible Surfaces

For further classification of *Partially-Accessible* surfaces, the outer edge boundary of the positive surface, shown using bold lines in Fig. 10(f), that is at the uppermost level of *B_Result2* in the positive direction, is compared with outer edge boundary of the considered surface. If the edges of the outer boundary edges overlap fully or partially when projected on a plane in the considered parting direction, then the surface is classified as *Partial-Outer-Boundary-Accessible*, otherwise, the considered surface is classified as *Inaccessible-Outer-Boundary*.

Fig. 10 depicts the accessibility analysis procedure for a *Partially-Outer-Boundary-Accessible* surface. It is observed that outer edge boundary of the uppermost positive surface of *B_Result2*, shown in Fig. 10(f), partially overlaps the outer boundary of the considered surface when their outer-boundary edges are projected on a plane in the parting direction. Whereas in Fig. 11, the outer edge boundary of uppermost positive surface of *B_Result2*, shown in Fig. 11(f), does not overlap the outer boundary of the considered surface, when their outer-boundary edges are projected in the parting direction. Therefore, the considered surface is of *Inaccessible-Outer-Boundary* type.

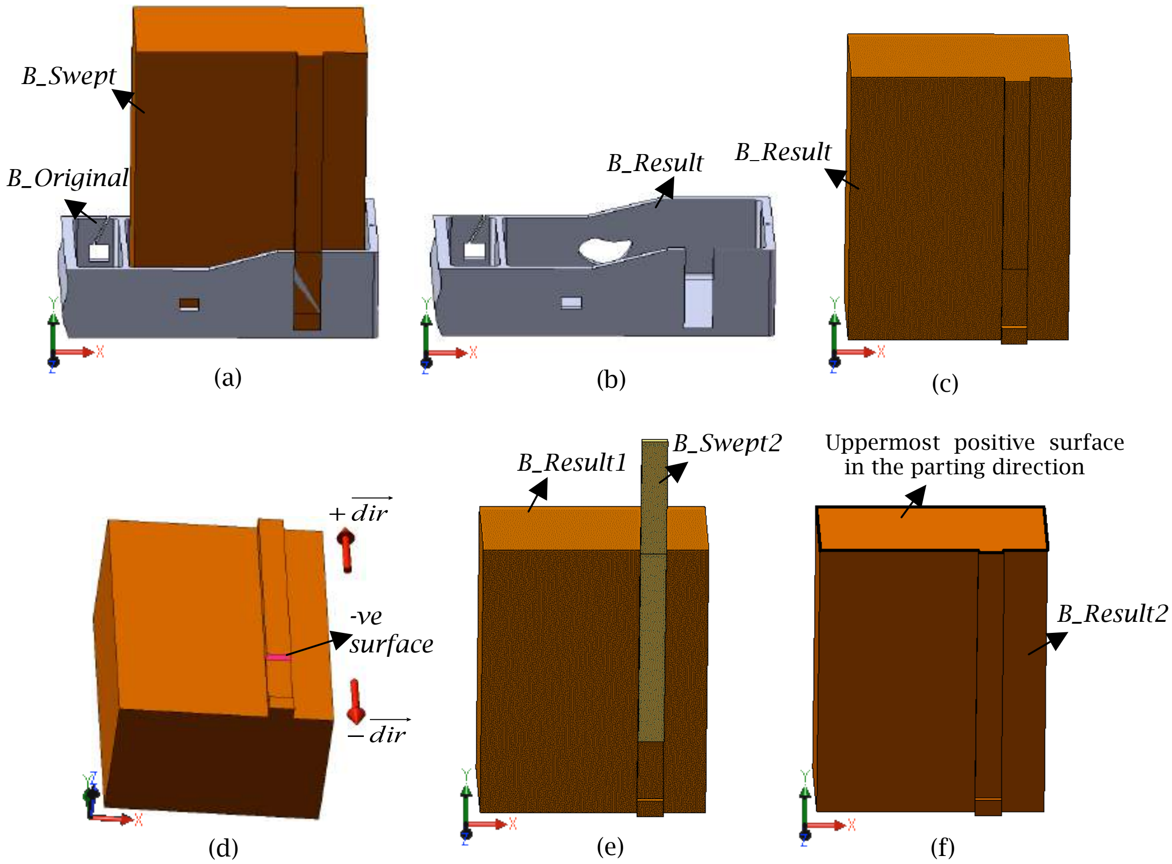


Fig. 10: Accessibility Analysis procedure for a *Partial-Outer-Boundary-Accessible* surface, demonstrated using surface *S4* of Fig. 6: (a) *B_Original* and *B_Swept1*, (b) *B_Result* as per Eqn. 1, (c) *B_Result1* as per Eqn. 2, (d) -ve surface of *B_Result1*, (e) *B_Result1* and *B_Swept2*, (f) *B_Result2* as per Eqn. 3

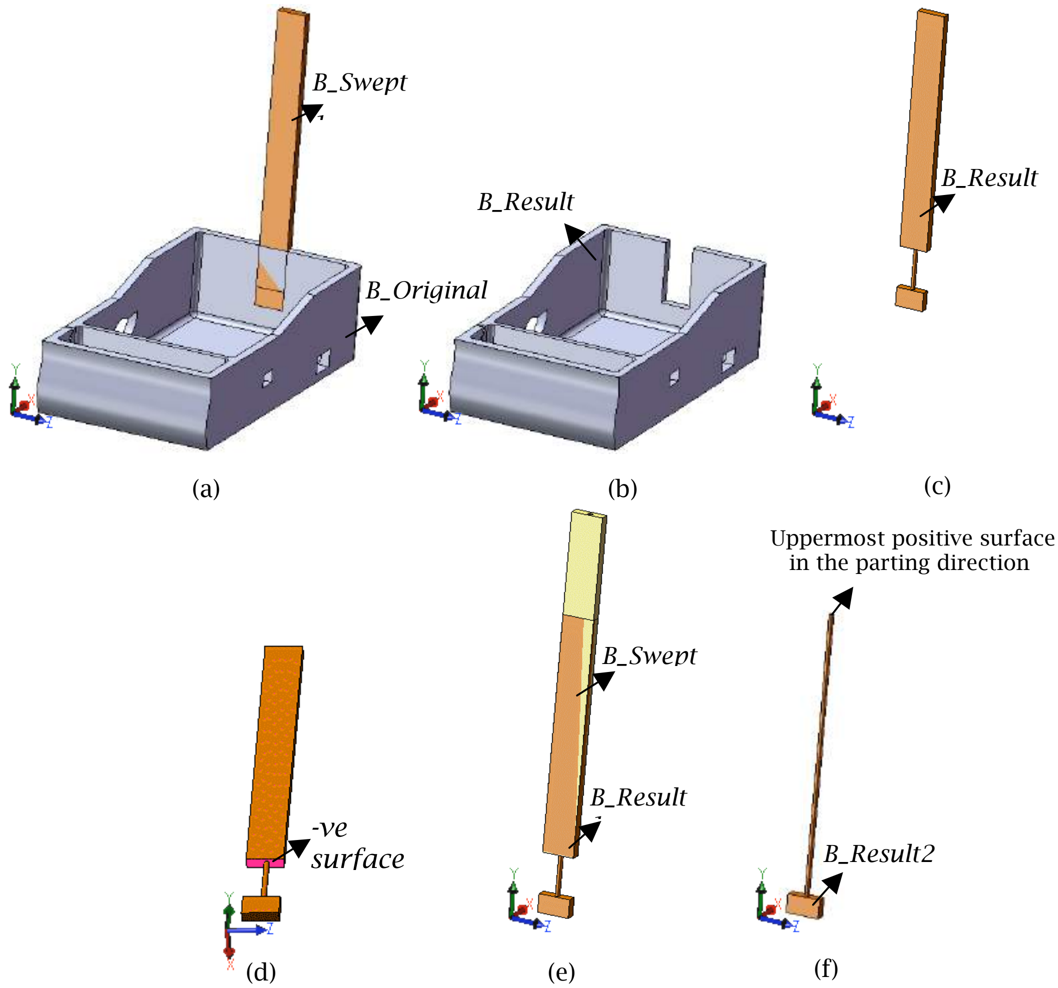


Fig. 11: Accessibility analysis procedure for an *Outer-Boundary-Inaccessible* surface, demonstrated using surface *S5* of Fig. 6: (a) *B_Original* and *B_Swept1*, (b) *B_Result* as per Eqn. 1, (c) *B_Result1 a*s per Eqn. 2, (d) *-ve* surface of *B_Result1*, (e) *B_Result1* and *B_Swept2*, (f) *B_Result2* as per Eqn. 3

6.2

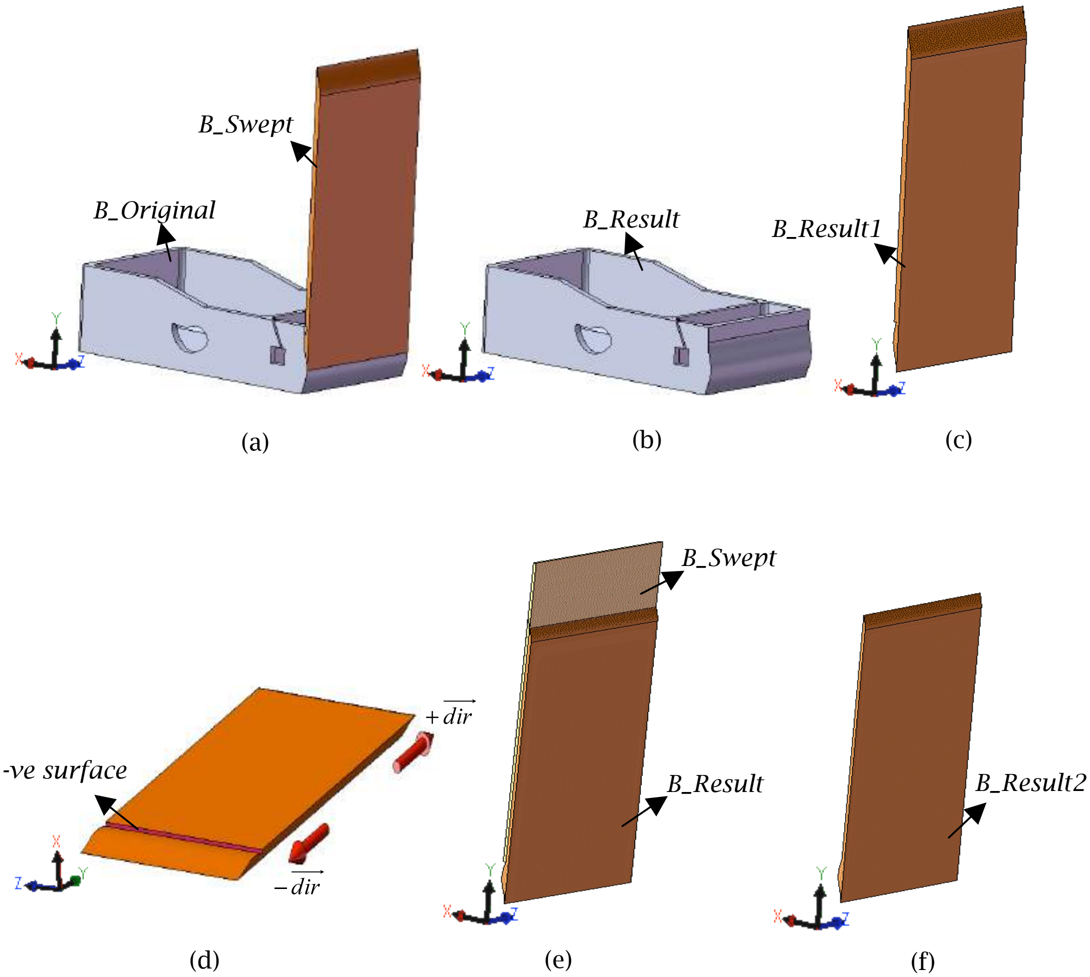


Fig. 12: Accessibility analysis procedure for a dual free-form surface, demonstrated using surface *S6* of Fig. 6: (a) *B_Original* and *B_Swept1*, (b) *B_Result* as per Eqn. 1, (c) *B_Result1 a*s per Eqn. 2, (d) *-ve* surface of *B_Result1*, (e) *B_Result1* and *B_Swept2*, (f) *B_Result2* as per Eqn. 3

6.3 Perpendicular Surfaces

Perpendicular surfaces can be accessible from positive as well as negative parting directions; therefore, these are analyzed in both of these directions. Moreover, a perpendicular surface might not be visible, but can be accessible. To determine the accessibility of the perpendicular surfaces, Priyadarshi and Gupta [9] slightly rotated the near-vertical facets of a STL part such that the near-vertical facet becomes a front-facet in the parting direction. Later, Priydarshi et al. [10] determined the accessibility of near-vertical facets by thickening the concave contour edges. The methodology developed to determine the accessibility of the perpendicular faces in the B-rep format is presented next.

6.3.1 Fully-Accessible Surfaces

To check the accessibility of considered surface from the parting direction $\pm\overrightarrow{dir}$, an offset surface is created at distant □ towards the outward surface normal of the considered surface, as shown in Fig.

13(a). The value of □ is decided by the minimum space required normal to parting direction to mold the part. The offset surface is thickened by amount □ towards the inward surface normal of the considered surface, as shown in Fig. 13(b), to generate a new solid body (*B_Offset*). The accessibility of positive and negative surfaces of *B_Offset* is evaluated to determine the accessibility of the perpendicular surface.

The surfaces of *B_Offset* are classified based on the orientation with respect to the considered parting direction $+\overrightarrow{dir}$. If the *B_Offset* has any dual surface, the surface is segmented into positive and negative surfaces using the silhouettes in the direction $\overrightarrow{dir}$.

To analyze the accessibility from $+\overrightarrow{dir}$ direction, all the positive surfaces of *B_Offset* are swept by a distance more than the maximum dimension of the part (say twice the maximum dimension) towards $+\overrightarrow{dir}$ direction. This operation results in a number of swept solid bodies that are represented as *B_Swept1*, *B_Swept2* …… *B_Sweptn*, as shown in Fig. 13(c). A regularized boolean operation is performed on these swept bodies as follows:

B_Combined= B_Swept1 + B_Swept2 +* B_Swept3+*……..+* B_Sweptn.* (4)

The resulting body, *B_Combined*, is the result of regularized boolean addition operation of all the swept bodies, shown in Fig. 13(d). Next, the accessibility analysis procedure for the perpendicular surfaces is similar to that of positive/negative surfaces if *B_Swept1* is replaced by *B_Combined*.

A regularized boolean subtraction operation is performed between *B_Original* and *B_Combined*, shown in Fig. 13(e), as per the following equation:

B_Result = B_Original - B_Combined.* (5)

If the resulting body (*B_Result*) has same volume as that of *B_Original*, then the considered perpendicular surface is classified as *Fully-Accessible* in the corresponding direction. For example, volume of *B_Result* and *B_Original* is same for the considered perpendicular surface in Fig. 13; therefore, it is classified as *Fully-Accessible*.

6.3.2 Fully-Inaccessible (Type1) Surfaces

If the perpendicular surface is not classified as fully accessible, then it is analyzed for full-inaccessibility and partial-accessibility from the considered direction. Similar to Eqn. 2 for positive/negative surfaces, a regularized boolean subtraction is utilized in which *B_Original* is subtracted from *B_Combined* as follows:

B_Result1= B_Combined - B_Original.* (6)

The above boolean operation may result in number of bodies depending on whether the surface is partially accessible or fully inaccessible. If *B_Result1* consists of two or more disjoined bodies, then it is concluded that surface is *Fully-Inaccessible (Type1)* from the considered direction; otherwise, the surface can be *Fully-Inaccessible* (*Type2*) or *Partially-Accessible*.

6.3.3 Fully-Inaccessible (Type2) and Partially-Accessible Surfaces

To determine if the considered surface is *Fully-Inaccessible* (*Type2*) or *Partially-Accessible*, the procedure adopted is same as that for the positive/negative surfaces, discussed in Section 6.1.3. The *Partially-Accessible* perpendicular surface are not further classified into *Partial-Outer-Boundary-Accessible* and *Outer-Boundary-Inaccessible* because a partially accessible perpendicular surface cannot be *Outer-Boundary-Inaccessible*.

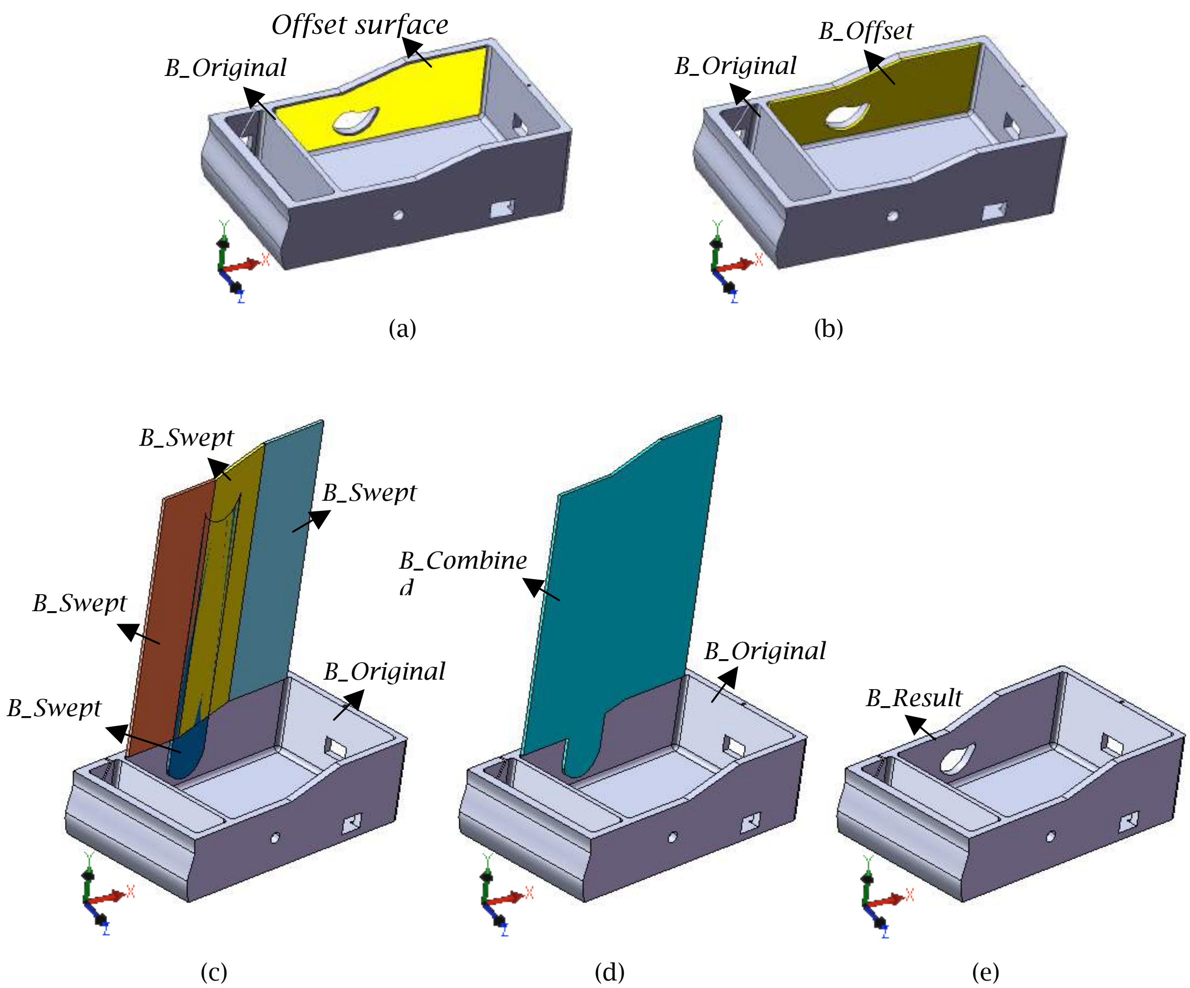


Fig. 13: Accessibility analysis procedure for a perpendicular surface, demonstrated using surface *S7* of Fig. 6: (a) *B_Original* and *Offset* surface, (b) *B_Original* and *B_Offset*, (c) *B_Original* and swept bodies, (d) *B_Original* and *B_Combined*, (e) *B_Result* as per Eqn. 5

7 DISUCSSION

The proposed methodology analyzes the accessibility of part surfaces, including perpendicular and free-form surfaces, in B-Rep format. The dual free-form surfaces are required to split into positive, negative and perpendicular using the silhouettes in the parting direction. Moreover, the numbers of steps involved in the accessibility analysis of *Partially-Accessible* are more than then numbers of steps involved in accessibility analysis of *Fully-Inaccessible* or *Fully-Accessible* surfaces. Therefore, the time taken of algorithm is proportional to the type and number of the part surfaces.

Furthermore, the method presented in this paper treats all surface entities in their algebraic form that differs from the methods based on tessellation which decomposes the part into small triangles and rely on linear computation to achieve time gains. However, for a part with sculptured surface, the tessellated triangles can be large in number; therefore, the computation time can be large. For the same part, the proposed method deals with fewer entities, but complex computations.

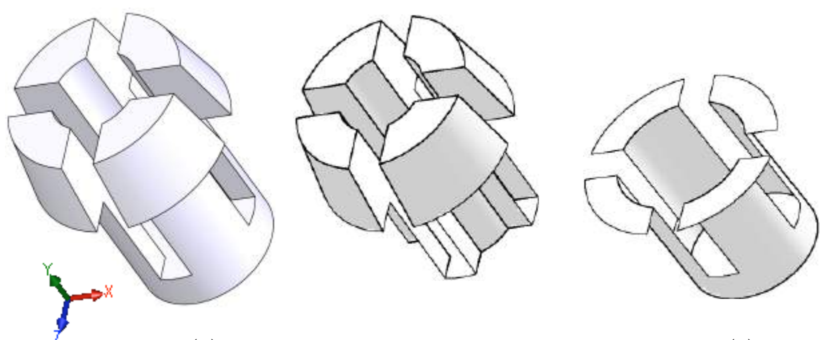
Based on the accessibility analysis, a direction is classified as undercut free if none of the part surface is obstructed in that direction. In other words, if all the part surfaces are classified as *Fully-*

Accessible in the considered direction, then the part can be molded without side-cores and side-cavities and the direction is undercut free.

8 IMPLEMENTATION

The present work has been implemented on Windows XP (Pentium 4 CPU 1.75GHz and 1GB RAM) using Microsoft Visual Basic and Solidworks. This algorithm has been tested on a variety of industrial parts having freeform as well as planar surfaces for accessibility analysis. As in most of industrial parts, it is observed that the parting direction is aligned along major axis of coordinate system. Each part has been tested for undercut free parting direction along the major axis.

The first case reported is a test part shown in Fig. 14(a). This part is geometrically similar to part considered by Dhaliwal et al. [3] and consists of 27 faces. The undercut free parting direction is successfully found along the *Y*-axis. The surfaces fully accessible from positive and negative side of the undercut free parting direction are shown in Fig. 14(b) and (c) respectively. The algorithm took 27s to analyze the accessibility and to determine the undercut free parting direction. The second case study, in Fig. 15(a), consists of 62 faces and is geometrically similar to the part considered by Priyadarshi et al. [10] for determining mold piece regions of a part. The algorithm took 52s to successfully determine the undercut free parting direction along the *Y*-axis. The surfaces shown in Fig. 15(b) and (c) are fully accessible from the positive and negative side of the *Y*-axis. The third test part shown in Fig. 16(a) is having 66 surfaces including freeform, planar and ruled. The algorithm took 69s to analyze the surface accessibility. This part is having undercuts along all the major axis. The surfaces that are fully accessible from the positive and negative *Y*-axis are shown in Fig. 16(b) and (c) respectively. However, there are some surfaces that are not fully-accessible from either side of the *Y*-axis, as shown in Fig. 16(d). Therefore, undercut free parting direction for this part is not found by the algorithm along any of the major axis.



(a) (b) (c)

Fig. 14: (a) Test case 1 from [3], (b) surfaces accessible from the + *Y*-axis, and (c) surfaces accessible from – *Y*-axis

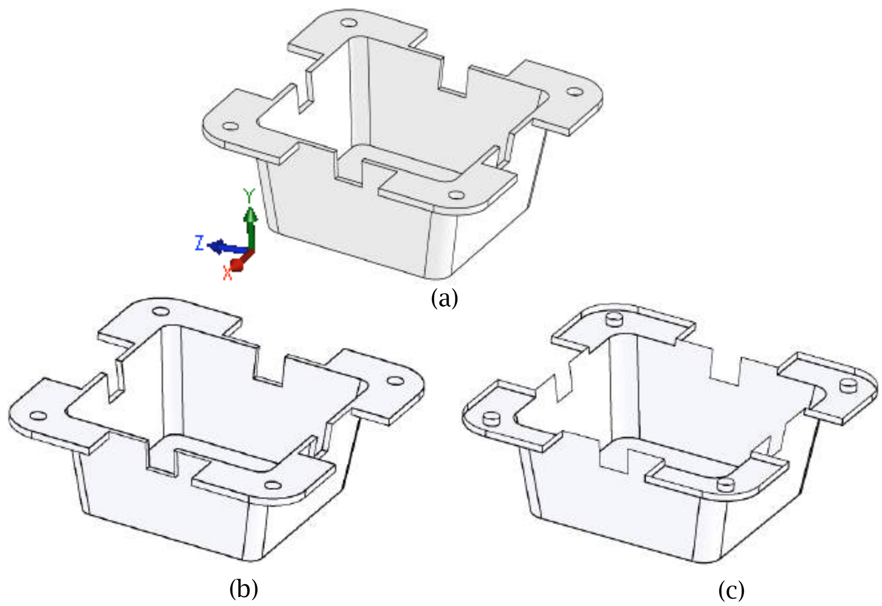


Fig. 15: (a) Test case 2 from [10], (b) surfaces accessible from the + *Y*-axis, and (c) surfaces accessible from – *Y*-axis

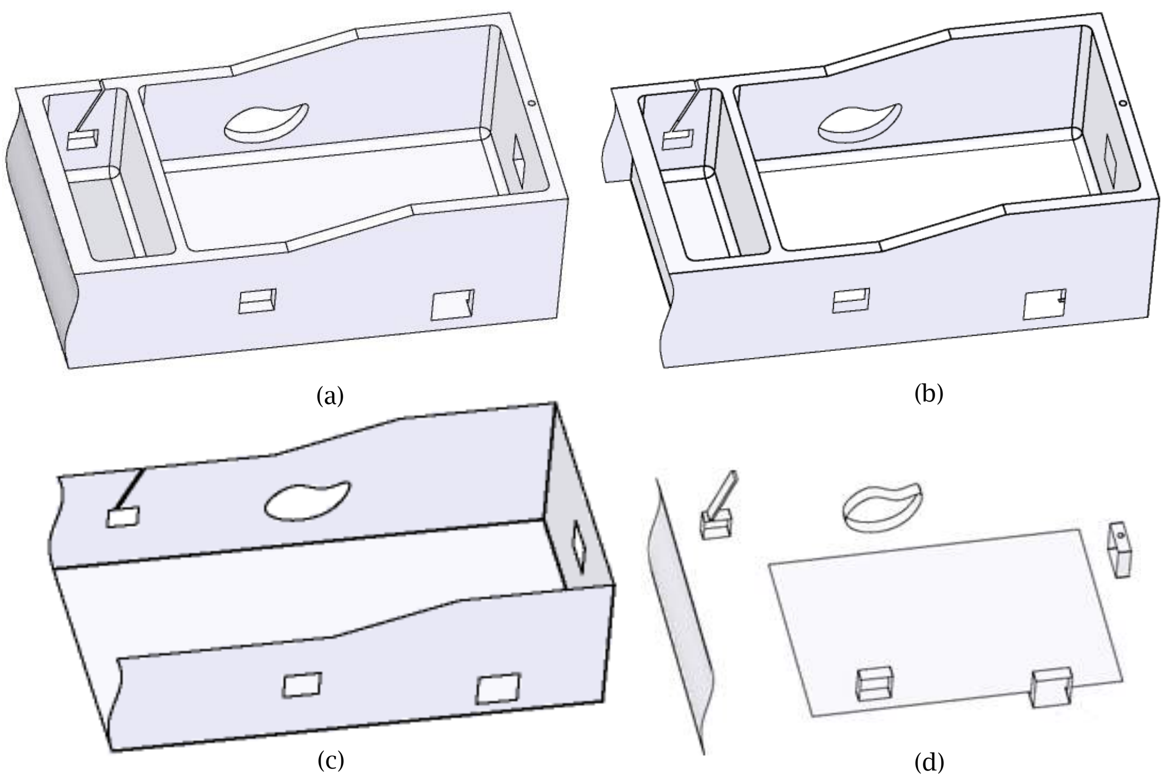


Fig. 16: (a) Test case 3, (b) surfaces accessible from the + *Y*-axis, (c) surfaces accessible from – *Y*-axis, and (d) surface not fully accessible from the *Y*-axis.

9 CONCLUSION

The proposed approach determines the demoldability of the part from a direction by using the accessibility level of the part surfaces from that direction. If all the part surfaces are fully accessible from the direction, then the part is demoldable from that direction without using the side cores. The presence of partially or fully inaccessible surfaces indicates the presence of undercuts. The computational time for the proposed approach is proportional to number of surfaces and type of surfaces. Whereas, in case of point based approaches, computational time depends upon the distance between the grid points. This algorithm can work for all kinds of surfaces using the regularized boolean operations. This concept can be further extended to generate the global visibility maps of the mold parts. As this concept is based on B-Rep model instead of STL format of solid, therefore chances of model error are unlikely.

REFERENCES

[1] Chen, L. L.; Chou, S. Y.; Woo, T. C.: Parting directions for mold and die design, Computer-Aided Design, 25(12), 1993, 762-768. doi:10.1016/0010-4485(93)90103-U

[2] Chen, L. L.; Chou, S. Y.: Partial visibility for selecting a parting direction in mold and die design, Journal of Manufacturing Systems, 14: Number 5, 1995, 319-330.

[3] Dhaliwal, S.; Gupta, S. K.; Huang, J.; Priyadarshi, A.: Algorithm for computing global Accessibility cones, Journal of Computing and Information Science in Engineering, 3, 2003, 200-209.

[4] Elber, G.; Cohen, E.: Arbitrarily precise computation of Gauss maps and visibility sets for freeform surfaces, The third ACM Symposium on Solid Modeling and Applications, 1995, 271-279.

[5] Hui, K. C.; Tan, S. T.: Mould design with sweep operations – a heuristic search approach, Computer-Aided Design, 24(2), 1992, 81-91. doi:10.1016/0010-4485(92)90002-R

[6] Khardekar, R.; Burton, G.; McMains, S.: Finding feasible mold parting directions using graphics hardware, Computer-Aided Design, 38, 2006, 327-341. doi:10.1016/j.cad.2006.01.008

[7] Kim, D. S.; Papalambros, P. Y.; Woo, T. C.: Tangent, normal, and visibility cones on Bezier surfaces, Computer-Aided Geometric Design, 12, 1995, 305-320. doi:10.1016/0167-8396(94)00016-L

[8] Nee, A. Y. C.; Fu, M. W.; Fuh, J. Y. H.; Lee, K. S.; Zhang, Y. F.: Automatic Determination of 3-D Parting Lines and Surfaces in Plastic Injection Mould Design, Annals of the CIIRP, 1998.

[9] Priyadarshi, A.; Gupta, S. K.: Generating algorithms for automated design of multi-piece permanent molds, Computer-Aided Design, 36, 2004, 241-260. doi:10.1016/S0010-4485(03)00107-6

[10] Priyadarshi, A. K.; Gupta, S. K.: Finding Mold-Piece Regions Using Computer Graphics Hardware, Geometric Modeling and Processing 2006, Lecture Notes in Computer Science, 4077, 655-662

[11] Woo, T. C.: Visibility maps and spherical algorithms, Computer-Aided Design, 26(1), 1994, 6-16. doi:10.1016/0010-4485(94)90003-5